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Regional suitability of virtual water strategy: Evaluating with an integrated water-ecosystem-economy index

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ABSTRACT

With growing populations and climate change, more regions around the world are prone to unprecedented water scarcity. The concept of virtual water is introduced in the Middle East, where one of the strategy to solve water scarcity is to import grain instead of grow grain locally. However, some researchers have argued that such virtual water strategy as a solution to water scarcity is fallacious failing to take regional socio-economic and environmental suitability into account. In this study, an evaluation index system of virtual water strategy was constructed from an integrated water–ecosystem–economy system perspective. The evaluation index system can reflect the co-relationship among water, ecosystems and the economy and the status of system, which consists of resources, technology, economy, society, and environment. Using the improved entropy weighting and fuzzy synthetic evaluation methods, regional suitability of virtual water strategy was assessed and classified into the following five grades: excellent, good, average, fair, and poor. Using the Heihe River Basin (HRB) as the case study area, the evaluation index system was applied to examine the regional suitability of virtual water strategy for each county in the river basin. Results showed the suitability degree of approximately half of the counties was 'excellent', while the other half was 'average', except for Jinta County whose suitability of the virtual water strategy was 'poor'. The results indicated that the suitability of the implementation of virtual water strategy is closely related to the economic development and ecological conditions. In addition, the study propels the evaluation of virtual water strategy, and enhances their persuasion in addressing water scarcity, identifying the feasibility in the arid and semi-arid regions worldwide.

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1. Introduction

Water is an essential natural resource for food production, industrial manufacturing, and ecological conservation. With increasing water demand worldwide, many regions are experiencing severe water scarcity (Hoekstra et al., 2012). Water scarcity has received much attention from researchers and policy makers worldwide (Hanasaki et al., 2013; Návar Cháidez, 2011; Návar, 2012; Zeng et al., 2013). The concept of virtual water was first introduced by Allan, who measured the total quantity of water embedded in a commodity or service (Hoekstra, 2003; Allan, 1998). The study also determined the quantity of water that was used for each stage of the production of goods and services within supply chains. Most of the world's water consumption is allocated to agricultural production. According to Gourbesville (2008), agricultural irrigation accounts for 70% of global water withdrawals during the past century. Therefore, the interregional trade in agriculture product can be considered as a substitute for water diversion projects. Some studies have concluded that water-scarce areas should import water-intensive agriculture products rather than produce them (Guan and Hubacek, 2007; Chen and Li, 2015; Katyaini and Barua, 2017). The concept is that water-embodied

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products should flow from water-abundant to water-scarce regions or countries to achieve sustainable water management. In addition to theoretical studies, many empirical studies have calculated virtual water flow to evaluated the impact of virtual water strategy on alleviation of water stress (Hoekstra and Mekonnen, 2012; Dalin et al., 2012; Zhang et al., 2011), or to clarify the link between economic growth, international trade, and water resource pressure thus contribute to the policy actions with water resource management (Duarte et al., 2016; Serrano et al., 2016).

Previous studies of virtual water have been quite divergent both in theory and application. Virtual water strategies are based on the economic theory of comparative advantage and the Heckscher-Ohlin trade model and is still under debate (Allan, 2003; Earle, 2001). The theory of virtual water has been criticized, because it is based on an incomplete understanding of comparative advantage in the production of water-intensive goods by assuming that land resources are more important determinants than water resources (Jia et al., 2017; Ansink, 2010). Some studies have argued that virtual water strategies neglect economic structure, total production factors, market function, and the future status of the agricultural sector in water-scarce regions (Merett, 2003). At the same time, other researchers have argued that virtual water cannot provide feasible solutions to fulfill the synergistic objective of sustainable water management, because it only considers the water consumption intensities of agricultural products and trade. Ansink (2010) assumed there are two incorrect claims regarding virtual water trade: it can level out the uneven water distribution, and it can reduce the potential for water conflict. Water is not the only resource required for economic development. The principal flaw in the virtual water strategy lies in that it only considers the marginal output of water but ignores sustainable economic growth. As a result, virtual water strategy is not necessarily suitable for all water-scarcity area. Furthermore, the above researches on virtual water strategy failed to engage the suitability of virtual water strategies from an integrated water–ecosystem–economy system perspective, leaving a huge gap in virtual water strategy assessment.

Virtual water strategies haves been used to formulate policies to improve water use efficiency at different scales. Such strategies have received increasing attention in the context of growing world population, economic growth and ecosystem health. Determining whether a certain region is suitable for implementing virtual water strategy is not easy. Some studies have suggested that water-scarce regions should resolve their water shortages by considering the interactions between hydrological processes and social–economic systems (Hoekstra, 2003; Allan, 1997; Rosegrant et al., 2002; Yang and Zehnder, 2002). Some studies have also concluded that virtual water strategies can attain a balance between sustainable water management and food security (Yang and Zehnder, 2007). Based on this argument, assessing the suitability of virtual water strategies is of great value to sustainable water resource management in water-scarce regions, especially arid areas (ZOU et al., 2009). Consequently, it is imperative to construct a comprehensive and practical evaluation index system, which integrates anthropogenic (production and domestic) and ecological water use, to assess the suitability of virtual water strategies in a region. Moreover, assessing the suitability of virtual water plays a crucial role in increasing water productivity and promoting integrated water resource management. Ultimately, assessing the suitability of virtual water can lead to a better understanding of water use contradictions among household consumption, agricultural and industrial production, and ecological protection. This can enable formulating policies for optimal allocation of physical and virtual water resources to achieve regional development goals for economic growth and ecological protection.

An evaluation index was developed in this study to evaluate the suitability of regional implementation of virtual water strategy from an integrated water–ecosystem–economy system perspective. The suitability of the virtual water strategy was determined, and case study is performed to demonstrate its potential application. First, we selected five specific components of the index: resource endowment, technology and transportation, economic development, social adaptation, and ecological environment, where the indictors included in Technology and Transportation, Economy and Society components correspond to perspective of economy, and the indictors included in Resources and Environment components correspond to perspective of water and ecosystem, respectively. The index was then applied for quantitative evaluation of the suitability of the virtual water strategy in the Heihe River Basin (HRB) in northwest China. Finally, we adopted the fuzzy synthetic evaluation approach based on an entropy weighting method to categorize and analyze the suitability of the virtual water strategy for each county in the river basin.

2. Methodology

2.1. The integrated water–ecosystem–economy system perspective

Liu proposed the concept of telecoupling to illustrated the importance of the interaction between socioeconomic systems and environmental systems (Liu et al., 2013). The implementation of the virtual water strategy can be determined by many factors from an integrated water–ecosystem–economy system perspective. Water is an essential resource that sustains ecosystems, economic systems, and human wellbeing. Regional ecosystem service functions affect economic development and sustainable livelihoods. Balancing water demand among ecosystems, human livelihoods, and economic systems is crucial for sustainable water management in a river basin. Therefore, the suitability assessment of virtual water strategy should not only consider water itself but expand to the coordination of the relationships among water resource sustainability, ecosystem health, and economic development through treating the basin as an integrated entity, with water being the central determining factor.

2.2. Suitability indicators

The index system was constructed in HRB to evaluate which counties are suitable to implement virtual water strategies. “Suitable” here means that the counties are capable of importing virtual water goods, and such import does not tend to impair household income. Meanwhile, water demand from ecosystem is also an essential part of water resource system, which is included in the index according. Hence, an integrated water–ecosystem–economy system is formulated. The index encompasses five components: resources, technology and transportation, economy, society, and environment, with each consisting of sub-elements (indicators) (Table 1**).** The resources component includes the following indicators: per capita water availability, water consumption per 10,000 Yuan of the value added by industry, per capita arable land, and per unit area grain yield.

The indicators in the resources component include the water abundance and water use efficiency, as well as land resources. Water quantity is an important indicator demonstrating water shortage. The more severe water shortage is, the more physical and virtual water is needed. Thus, the degree of water shortage is one of the most important indicators to evaluate the suitability of the virtual water strategy. Per capita water availability was used to represent the degree of water shortage. Water-use efficiency will also affect the water demand. It is presented by water consumption per 10,000 Yuan of the value added by industrial water

Table 1
The integrated evaluation index system.

Component/Indicator	Description
Resources	
Per capita water availability	The surface and ground water availability (m^3/person)
Water consumption/ 10,000 Yuan of value added by industry	$\frac{\text{Total amount of industrial water usage (in a county)}}{\text{Total amount of industrial value} - \text{added (in a county)}}$ ($m^3/10^4$ Yuan)
Per capita arable land	Total annual area of arable land in a county (hm^2/person·year)
Grain yield per unit area	$\frac{\text{Total amount of grain output (in a county)}}{\text{The actual area of arable land consumed by food crops (in a county)}}$ (ton/hm^2)
Technology and Transportation	
Industrial efficiency	Industrial technical efficiency under a variable return to scale
Irrigation coefficient	$\frac{\text{Amount of the net water yield absorbed by crop}}{\text{Total amount of irrigation water introduced}}$
Freight turnover	The product of freight tonnage carried and transport distance (10^3 t·km)
Transport network density (Jin et al., 2010)	$\frac{\text{The length of transport facilities (in a county)}}{\text{The area of the county}}$ (km/10^2 km^2)
Economy	
GDP per capita	Per capita GDP of a county (Chinese Yuan)
GDP growth rate	The ratio of the difference between the GDP of the target year and the GDP of the previous year (%)
Agricultural gross ratio	Agricultural annual gross value as a percentage of total annual GDP in a county
Grain self-sufficiency ratio	$\frac{\text{Total amount of grain output(in a county)}}{\text{Total amount of grain demand(in a county)}}$ (%)
Society	
Engel coefficient	The proportion of income spent on food (%)
High school diploma ratio	The proportion of the population aged > 6 years with a high school diploma (%)
Urbanization rate	Urban gross population as a percentage of total population in a county (%)
Population growth rate	$\frac{\text{Total annual number of natural growth population (in a county)}}{\text{Total annual number of average population (in a county)}}$ (‰)
Environment	
The proportion of ecological water consumption	The proportion of ecological water use among the total water consumption (%)
Forest-grass cover (Kumar and Singh, 2005)	Forest and grass land as a percentage of the total land area in a county (%)
Habitat quality index (HQI) (Kumar and Singh, 2005)	$\frac{0.35 \times \text{forest land} + 0.21 \times \text{grass land} + 0.28 \times \text{water wetland} + 0.11 \times \text{arable land} + 0.04 \times \text{construction land} + 0.01 \times \text{bare land}}{\text{The area of the county}} \times A_{bio}$ A_{bio} is the normalization coefficient of the HQI, with a reference value of 511.26.

consumption. When virtual water strategy is implemented, proportion of agricultural water use will be reduced. The arable land resource is the basis of food production. Some studies have indicated that crucial factors driving virtual water flow are the quantity and quality of arable land (Kumar and Singh, 2005). Therefore, the per capita arable land and grain yield per unit area were also used as indicators.

The indicators for technology and transportation were based on the technological level of industrial production and the level of transportation convenience. According to Allan, Virtual Water Strategy can reduce water consumption through trade of agricultural products, and transfer the water resources to the secondary and tertiary industries, which can achieve higher added value (Carroll et al., 2004). But if a water-scare county has no absolute advantage in secondary and tertiary industries, there will be simply no money to import food, rendering the virtual water strategy unsuitable. Although their resource use may be similar, the technological levels of agricultural and industrial production should be assessed respectively. Therefore, we used industrial efficiency and an irrigation coefficient as indicators of technological levels. Additionally, the food trade is obviously restricted by economic and natural factors. A good transportation infrastructure is a necessary condition for implementation of the virtual water strategy. We selected freight turnover and transport network density to express regional transportation.

The economy component included indicators for the level of economic development and the condition of product self-sufficiency. In general, water consumption in the agricultural sector is greater than that in the industrial or service sectors. According to comparative advantage theory, the core of the virtual water strategy is that water-poor areas can ease the demand on agricultural water use by means of food imports. During this process, the implementation of the virtual water strategy requires a certain economic capacity to purchase food products. Under the same conditions, the suitability of a country or region to implement the virtual water strategy is correlated with the level of economic development. The degree of food (mainly grain) self-sufficiency in a region therefore needs to be evaluated. If there are high degrees of food self-sufficiency and high levels of existing food exports in water-scarce regions, it will be difficult to implement virtual water strategy. Adoption of the virtual water strategy would encourage regional industrial transformation, thus accelerating economic growth. Therefore, the degree of diversification in the economy also reflects the suitability of the virtual water strategy. In this study, we

selected GDP per capita and the GDP growth rate to evaluate the level of economic development. In addition, agricultural gross ratio and grain self-sufficiency ratio were used to assess the level of economic diversification and the condition of product self-sufficiency, respectively.

The society indicators express the adaptive capacity of the region in terms of water shortages and the ability to tolerate risks. The implementation of the virtual water strategy will inevitably influence the integrated water–ecosystem–economy system. Abundant social resources and rapid response to the impact could lower the risks and benefit the region more. The virtual water strategy may generate unemployment. Higher levels of educational achievement will improve an individual's opportunities in labor markets by enabling easier transfer between industries. The proportion of the population with a high school diploma was therefore used as an education indicator. Urbanization provides opportunities and possibilities for labor migration from the agriculture to industrial and service sectors and thus was also included as an indicator. We used the population growth rate to represent the regional population burden, which is positively related to food demand. In addition, the Engel coefficient was used to reflect the living standard of a country or region.

The environment component contained ecological water allocation and ecological background indicators. The virtual water strategy can optimize water allocation to obtain a balance between agricultural production and environmental protection. The virtual water strategy also impacts positively on local biodiversity by decreasing the area of cultivated land. Therefore, the proportion of ecological water consumption, area under forest-grass cover, and the habitat quality index were used as indicators to measure ecological health.

2.3. Assessment method

The evaluation of the suitability of virtual water strategy is an empirical study that artificially grade the suitability based on the comprehensive calculation of total influencing indexes. It means that the suitability is determined by a variety of factors, and the relationships among the factors are uncertain. The degree of influence of each factor is different, but there is some relatedness among them, i.e., the influencing factors and factor boundary conditions are uncertain. Therefore, the evaluation of virtual water suitability is a multi-objective and multi-level fuzzy evaluation problem. Many classical mathematical evaluation models are applied in terms of suitability evaluation, such as analytic hierarchy process, principle component analysis (Wu et al., 2011; Carroll et al., 2004), etc. However, those methods are inadequate in assessing the uncertainty when tackling a problem. Compared to classical set theory by Zadeh (1965) introduced the concept of fuzzy sets, and he proposed the concept of "membership function" to describe the intermediate transition of phenomenological differences, thus breaking through the absolute relationship with belong or not in classical set theory. Fuzzy comprehensive evaluation method is a multilayer comprehensive evaluation index system based fuzzy mathematics, which has been applying in many evaluation systems in the latter scientific research (Yang and Mak, 2017; Dunwen et al., 2012; Delgado and Romero, 2016). The procedure of fuzzy comprehensive evaluation is as follows (Fig. 1): a) construct the set of evaluating factors. b) establish the evaluation set, which is the set of all possible evaluation results for the evaluation object. c) confirm the membership function. d) establish the fuzzy relationship matrix based on the entire single factor evaluation. e) determine the weight set of the indices. f) construct the fuzzy evaluation matrix based on the d) and e), and then get the evaluation results by fuzzy arithmetic operator.

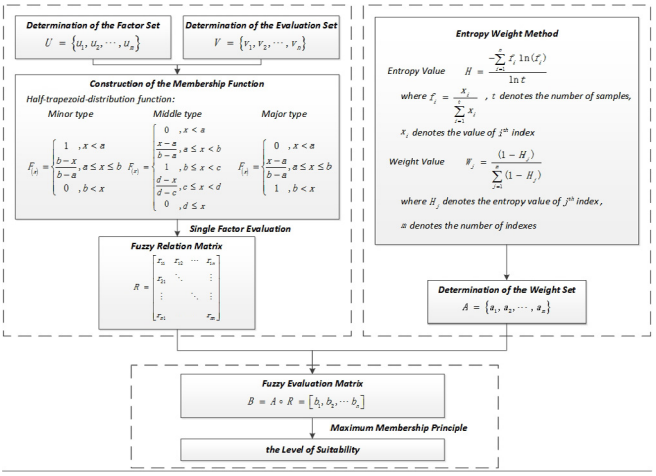

Fig. 1. Flowchart of the fuzzy synthetic evaluation method. Notes: A max–min algorithm (i.e., Zadeh algorithm) was used as the fuzzy arithmetic operator. In matrix B (shown in Table 4), if there were two maximum membership values, then the evaluation level was defined according to the value closer to the level of the secondary maximum.

The determination of weighting is an important step in the fuzzy synthetic evaluation, because it is a crucial parameter influencing the evaluation results. Criteria weights, such as AHP method (Sutadian et al., 2017), Delphi method (Yoon et al., 2000; Strand et al., 2017), etc., are usually assigned according to expert opinions, and this may cause a subjective bias. The entropy weighting method was first used in the field of thermodynamics and was later introduced into information theory by Shannon (2001). It is used to determine the index weighting of the judgment matrix, which is based on the index value of the evaluated object. The strong objectivity can eliminate the influence of subjective factors, such as expert opinions. When the evaluated object has the same value at two different indicators, the maximum entropy value is 1, while an entropy weighting of 0 means that the indicator does not provide any useful information to decision makers. When the difference in the index value of each evaluated object in certain indicators is large, the entropy value is small. A large entropy weighting means that the indicator provides more useful information to the decision maker. The entropy weighting method was used in this study to determine the index weighting of the indicators in the fuzzy synthetic evaluation.

Another important part of the fuzzy synthetic evaluation is determination of the evaluation set and membership function. The degree of suitability of the virtual water strategy is relatively obscure. For a single evaluation indicator, it is not possible to use "yes" or "no" to determine which evaluation set it belongs to. Therefore, for a quantitative evaluation index, a value between 0 and 1 (including 0 and 1, [0,1]) was used to represent the magnitude of the evaluation factor to the uncertainty of the membership of the evaluation set, i.e., the membership degree. When the membership degree changes due to variable change, establishment of a membership function is needed. Based on the basic principle on of membership function and the membership degree analysis, the virtual water suitability evaluation factor was constructed. At the same time, the fuzzy distribution conforms to the trapezoidal distribution mainly. Therefore, the half-trapezoid-distribution function was used in this study (Qiongfang and Yingsong, 2003). Finally, the result was allocated into one of five grades in accordance with the likelihood and degree of suitability of implementation of the virtual water strategy, namely an evaluation set $V = \{\boldsymbol{I, II, III, IV, V}\}$ = {excellent, good, average, fair, and poor

suitability, respectively}. In other word, the results of assessment are divided into five grades, which are named grade ***I, II, III, IV*** and ***V*** respectively, and for each county, the suitability of implementation of the virtual water strategy will be getting lower as the evaluation results declined from ***I*** to ***V***. Each county will eventually get one of the five grades by calculated, in order to estimate the level of suitability of virtual water strategy in the county.

3. Case study

3.1. Study area

River basin is considered ideal unit for managing water, land, and other resources, since it represents a coupled natural-human system (Cheng and Li, 2015). In this study, we used the HRB, the second largest inland river basin in China as the case study area. The HRB is located in the middle of the Hexi Corridor, which is an arid/semi-arid region (Fig. 2). This basin has experienced serious water scarcity and ecological damage. The Heihe River originates from the Qilian Mountains in the northern margin of the Qinghai-Tibet Plateau and runs ultimately into the Juyan Lake following a south to north route through the Hexi Corridor. The characteristics of the terrain and ecosystems in the basin are diverse, ranging from alpine ecosystems in the southern Qilian Mountains, oasis towns in the middle reaches, to deserts in the northern downstream area. The total length of the Heihe River is 821 km, and the river basin covers an area of 142.9 thousand km^2. Administratively, the three reaches are located in different provinces. The upstream is in Qilian County of Qinghai province, the middle reach is in Zhangye city, Suzhou district and Jiayuguan City of Gansu province, and the downstream is in Jinta County of Gansu Province and Ejin Banner of Inner Mongolia. In this study, we evaluated the suitability of the virtual water strategy in each county in the HRB.

The main problem currently facing the HRB is the water demand competition between economic activities and ecological protection. In the upper reaches, Qilian County is mainly covered with forest and grass, having a relatively smaller urban population and less industrial activity than those of the other parts of the basin. Precipitation in this region is abundant, and there is little difference between water supply and demand. Because of the large area of forest and grass cover in Qilian County, it is one of the important animal husbandry bases in Qinghai province. Most human and economic activities in the basin occur in the middle reaches in the Central Oasis of Gansu Province, where water consumption by economic activities is considerable. Agriculture accounts for more than 90% of the total water consumption in the middle reaches. Ejin Banner in the downstream area is mainly gobi and grass land, and it used to be a natural barrier to sandstorms. The region has experienced rapid socioeconomic development and urbanization in recent years, which has led to serious degradation of the ecological environment. Because a large proportion of the basin's water is used in the middle reaches, limited amounts are available for downstream areas. In 1997, a water reallocation plan was initiated by the State Council of China to divert water from the middle reaches and restore the ecological environment downstream (Wu and Zhan, 2015; Deng et al., 2014). Large differences between water supply and demand are apparent among the different counties in the HRB. The application of virtual water strategy to the HRB is one of the effective ways to solve the contradiction between supply and demand of water resources in the basin. According to Allan's virtual water strategy, one of the essential conditions (the other is the lack of water and soil) for its application is whether the water-scare regions have an absolute advantage in technology and other conditions (with sufficient funds) to import cereal products. So, for all counties in HRB, because of the differences of technical level and resource conditions among them, it's significant to put forward the evaluation index to assess whether all counties are suitable to implement the virtual water strategy.

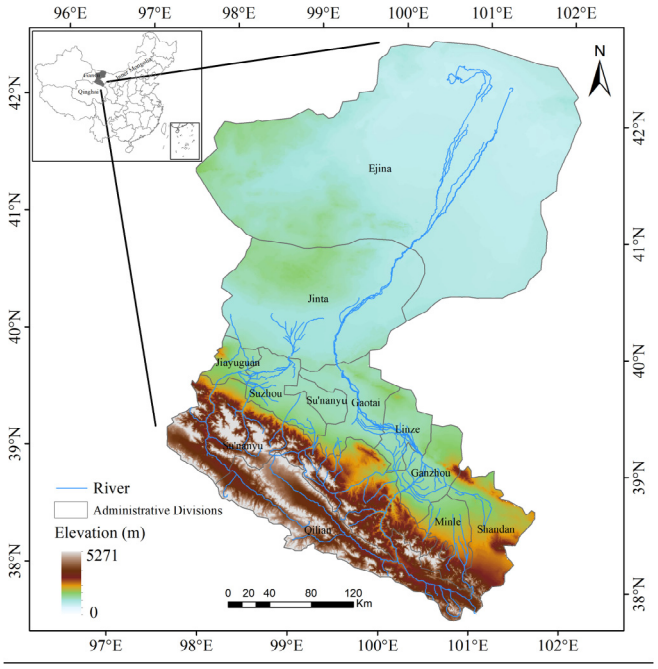

Fig. 2. Study area: the Heihe River Basin (HRB). Notes: Red, brown, blue, green and yellow grid cell represents grade **I, II, III, IV** and **V**.

3.2. Data sources

To select appropriate indicators and construct an integrated evaluation index is important for the suitability assessment of virtual water strategy. In this case study, we collected statistical data and geographic information to evaluate the suitability of virtual water strategy in each county in the HRB. In this study, original data were processed for each of the indicators. The indicator data included water resources, agricultural production, and demographic and economic information. Statistical data were obtained from statistical yearbooks and the Water Resource Bulletin. Geographic information data, including traffic network information and land use information of the HRB, were obtained from a regional database (http://westdc.westgis.ac.cn/). And all data were from the year in 2012. The statistics information of these variables for 11 districts and counties in HRB for 2012 are presented in Table 2.

4. Results and discussion

4.1. Statistical analysis of the level of suitability

The evaluation index used to determine the suitability of the virtual water strategy in the HRB was established using five components: resources, technology and transportation, economy, society, and environment. Using the improved entropy weighting method, the weighting of the 19 indicators for each county were calculated (Table 3). The resources component had a pivotal position in five evaluation subsystems and had the maximum weighting value. Among the four indicators of the resources component, water quantity was undoubtedly the most influential factor. The suitability of the virtual water strategy for a region is first determined by the degree of water shortage. The weighting values of the remaining three indicators in the resources component were much

Table 2
Statistical data for the indicators used in this study.

Indicators	Mean	Min	Max	SD
Resources				
Per capita water availability (m^3/person· year)	3436.07	434.53	22926.80	6206.98
Water consumption/10,000 Yuan of value added by industry (m^3)	58.00	11.00	98.00	24.86
Per capita arable land (hm^2/person · year)	0.16	0.01	0.26	0.08
Grain yield per unit area (ton/hm^2)	3.71	0.43	7.11	1.83
Technology and Transportation				
Industrial efficiency	0.64	0.31	1.00	0.25
Irrigation coefficient	0.54	0.41	0.58	0.05
Freight turnover r (10^3 t·km)	90862.05	6934.00	346960.00	105682.07
Transport network density (km/10^2 km^2)	29.67	6.31	61.52	14.37
Economy				
GDP per capita (Chinese Yuan)	60730.00	14945.00	253412.74	66983.81
GDP growth rate (%)	15.73	10.40	26.10	3.90
Agricultural gross ratio (%)	14.93	1.50	30.44	10.55
Grain self-sufficiency ratio (%)	150.47	11.00	268.41	95.68
Society				
Engel coefficient (%)	38.27	30.18	50.84	4.68
High school diploma ratio (%)	14.14	9.00	24.75	4.71
Urbanization rate (%)	41.26	20.93	89.82	19.33
Population growth rate (‰)	0.63	0.26	1.43	0.31
Environment				
The proportion of ecological water consumption (%)	21.90	0.92	67.65	18.26
Forest-grass cover (%)	24.97	4.84	57.45	19.40
Habitat quality index (HQI)	42.85	9.45	77.80	24.34

Table 3
The suitability of the virtual water strategy according to the integrated evaluation index.

Component	Weight	Indicators	Weight
Resources	0.2482	Per capita water availability (m^3/person· year)	0.3799
		Per value added industrial water consumption (m^3/10^4 yuan)	0.2114
		Per capita arable land (hm^2/person··year)	0.1979
		Grain yield per unit area (ton/hm^2)	0.2108
Technology and Transportation	0.1884	Industrial efficiency	0.2670
		Irrigation coefficient	0.2272
		Freight turnover (10^3 t·km)	0.2412
		Transport network density (km/10^2 km^2)	0.2646
Economy	0.1940	GDP per capita (Chinese Yuan)	0.2194
		GDP growth rate (%)	0.2394
		Agricultural gross ratio	0.2662
		Grain self-sufficiency ratio (%)	0.2750
Society	0.2053	Engel coefficient (%)	0.3271
		High school diploma ratio (%)	0.2319
		Urbanization rate (%)	0.2204
		Population growth rate (‰)	0.2206
Environment	0.1641	The ratio ecological water consumption (%)	0.3851
		Forest-grass coverage (%)	0.2929
		Habitat quality index	0.3220

smaller. Water use efficiency and the quantity and quality of the cultivated land had equal influences on the suitability of the virtual water strategy. Among the five components, the weighted values of society, economy, and technology and transportation followed a descending order. This indicated that society component including social adaption ability and the capacity to resist risks were more important for determining the suitability of the virtual water strategy than were the economy and the technology and transportation components. Therefore, the Engel coefficient, high school diploma ratio, food self-sufficiency rate, and industrial technology efficiency should be given priority when evaluating the suitability of the virtual water strategy. The weighting of environment was the smallest of the five components, but this does not mean that the environment component should be ignored. Finally, in general, the suitability of the virtual water strategy did not vary, even though the weightings of all indicators in the five components were

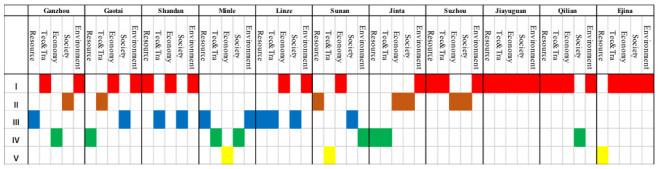

Fig. 3. Level of suitability of the five components of the evaluation index in each county.

different. This confirms that the suitability of the virtual water strategy is determined from multiple perspectives.

After determining the weighting of each indicator, we classed each of these components into one of five grades. Each county was classified into 5×5 grid cells. The intensity of color in the grid square of each county represents the coordinated development of

Table 4
A comprehensive assessment of the suitability of the virtual water strategy at the county level.

County	I	II	III	IV	V	Suitability
Ganzhou	0.2053	0.2053	**0.2482**	0.2482	0.1249	Average
Gaotai	0.2108	0.2053	**0.2482**	0.2482	0.1979	Average
Shandan	**0.2482**	0.2327	0.2053	0.1940	0.2402	Excellent
Minle	0.2108	0.2053	**0.2482**	0.2053	0.1979	Average
Linze	0.2053	0.2071	**0.2482**	0.1884	0.2482	Average
Sunan	0.2108	**0.2482**	0.2134	0.2482	0.1884	Good
Jinta	0.2108	0.2053	0.1991	0.2053	**0.2114**	Poor
Suzhou	**0.2482**	0.2053	0.2053	0.0377	0.2114	Excellent
Jiayuguan	**0.2482**	0.2482	0.1884	0.0646	0.1940	Excellent
Qilian	**0.2482**	0.0351	0.2053	0.2053	0.1940	Excellent
Ejina	**0.2482**	0.1940	0.0682	0.0000	0.2482	Excellent

the area in the integrated water–ecosystem–economy system. In Fig. 3, the columns represent the grade of a single indicator, and the rows represent each of the components. As can be seen from Table 4, almost counties showed excellent suitability of virtual water strategy in environment component. The grading of the resources component was very different among counties. The economy component for Minle, technology and transportation component for Sunan, and resources component for Ejina were classified as grade V, meaning that they were relatively poorly qualified (Fig. 3). Because all five components in Jiayuguan and four components in Qilian and Ejina were classified as grade I, these counties showed the excellent suitability in those respective components.

The fuzzy synthetic evaluation of the 11 counties in the HRB was calculated. For almost half of the counties, the suitability was grade I, and for the other counties, both grades II and III were observed, except for Jinta County (Table 4), which means that the suitability of virtual water was excellent in half of the counties, and was good or average in other counties except for Jinta County. There were no counties classified as grade IV. These results indicate that the suitability of the virtual water strategy was generally good for the HRB. Except for Jinta County, most counties could attain the optimal conditions for implementation of the virtual water strategy by improving specific evaluation indicators. In conclusion, the suitability of the virtual water strategy for the HRB was relatively good.

The comprehensive and single-aspect distribution of the suitability of the virtual water strategy was calculated using the fuzzy synthetic evaluation method. Radar maps were used to analyze the distribution of multidimensional information. From the radar maps, factors affecting the suitability of the virtual water strategy, such as economic development and the level of technology, were demonstrated intuitively. The 11 counties were classified according to their level of suitability: higher, average, and lower suitability (Fig. 4). The gray areas in the radar maps indicate the average level of suitability, and the area enclosed by counties represent the comprehensive level of suitability respectively in another perspective. The larger the area in the counties, the higher the comprehensive level of suitability of the virtual water strategy. In

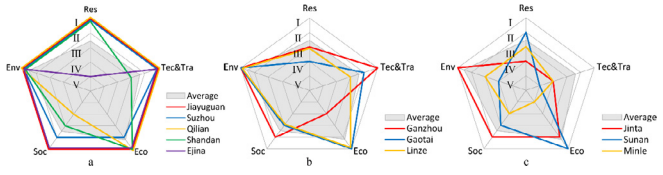

Fig. 4. The level of suitability of the virtual water strategy for 11 counties in the Heihe River Basin (HRB). Notes: "Res", "Tec&Tra", "Eco", "Soc", and "Env" indicate resources, technology and transportation, economy, society, and environment respectively.

other side, the gray area represents the average level of suitability of virtual water strategy all over the HRB, which results manifested the average level of suitability was generally grade II or III in the HRB.

Almost all counties showed larger physical area than the gray area in the radar maps, which was consistent with the results of the comprehensive suitability of the five counties. The level of suitability of the five components were all grade I in Jiayuguan, which was the most suitable region to deploy the virtual water strategy in the HRB. Jiayuguan is a typical industrial city, and among the 11 counties, its industrial technical efficiency is particularly prominent. The industrial development of Jiayuguan provides enough capital to import food to resolve the water scarcity problem. The average education and urbanization levels in Jiayuguan rank first among the 11 counties. This indicates that Jiayuguan could mitigate the risks caused by industrial transformation from implementation of the virtual water strategy. For Qilian County, the level of suitability of the society component was fair, and therefore could be improved based on grade IV at present. The water shortage problem could also be resolved by optimizing the available resources. For example, the levels of suitability of these five counties represented grade I were all excellent. The implementation of water-saving technologies would therefore be a better solution than enhancing agricultural water use efficiency. The development of secondary and tertiary industries will be encouraged by water saving, which will help balance regional economic development and ecological protection.

Three counties (Ganzhou, Gaotai, and Linze) showed average suitability. These three counties could also resolve their water shortages by implementation of the virtual water strategy. For example, Ganzhou could promote economic development by the development of ecotourism. Water saved in agriculture could be used to meet ecological water consumption or to grow agricultural products with low water consumption and high yields. By transferring water from traditional agricultural production to water-efficient agriculture or ecological protection, the joint development goal of economic growth and ecological protection could be achieved and a positive feedback cycle of regional sustainable development established.

Jinta County had the lowest suitability for the virtual water strategy. Whereas, the area enclosed by Jinta County was not much smaller than the gray area. By analyzing the level of suitability of the components, the suitability of the environment component represented grade I was excellent, but the weighting of the environment was only 0.16. Therefore, the contribution of the environment component to potential improvements in the suitability of the virtual water strategy was smaller than those for the other components. The per capita available water was approximately 2377 m^3 in 2012, which was the highest level of all the counties. In other words, the water demand was not as high in Jinta County as in the other counties. The per capita available water resources in Sunan County were only 878.15 m^3 in 2012, i.e., just one-quarter of the average level in the HRB. However, the agricultural water demand was smaller in Sunan County than in the other counties, and the population density was much lower.

4.2. Spatial distribution of the suitability of the virtual water strategy

To understand the spatial distribution of the suitability of the virtual water strategy in the HRB, the spatial variability of suitability was analyzed at the county level. The spatial distribution of the five components and the level of suitability of the virtual water strategy clearly differed across the HRB (Fig. 5). The lighter the color in the figure, the higher the suitability of the virtual water strategy

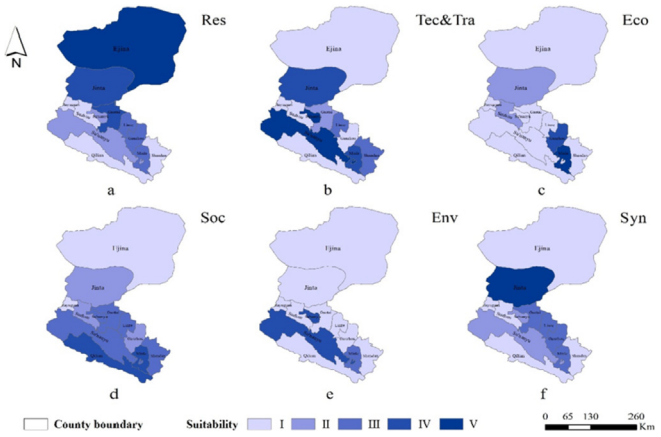

Fig. 5. Spatial distribution of the suitability of the virtual water strategy in the Heihe River Basin (HRB). Notes: (a), (b), (c), (d), (e) and (f) indicate resources, technology and transportation, economy, society, environment, and the level of synthetic suitability respectively.

in the county. We found that the resource endowment was higher in the upstream regions than in the middle reaches and downstream area. The spatial differences in the suitability of the virtual water strategy across the entire basin were not consistent with the resources component. The spatial distribution of the suitability of the virtual water strategy was determined by a comprehensive evaluation of the status of the water–ecosystem–economy system. Jiayuguan, Suzhou, Qilian, and Ejina were the most suitable counties for adoption of the virtual water strategy in the HRB. The virtual water strategy was more suitable in regions with a low population and high level of economic activity.

4.3. Discussion

The virtual water strategy is an effective tool for reallocation of global and local water resources. In this study, counties in the HRB were selected as research units, because these administrative units have decision-making power and can respond quickly to policy implementation. Although the evaluation of more relevant indicators in each subsystem would make the results more objective and reliable, the number of accessible indicators in each subsystem was specifically limited. The fundamental purpose of the study was to provide a pathway to identify the suitability of virtual water strategy, therefore, selection of indexes in this paper followed the principle of "fewer but better". Moreover, the criterion of suitability evaluation was accurately determined, with possible dynamic changes of suitability in the future. To deal with the fuzzy boundaries of evaluation criterion and make the evaluation results more objective, the membership function of the fuzzy synthetic evaluation method was used to describe the boundaries of suitability.

A method was devised to determine the suitability of the virtual water strategy at the basin level, and a case study was performed in the HRB. With regard to the availability of data, evaluation results using regional multi-year average data are more reliable than those obtained using data from a single year. Water availability per capita was used as the indicator of water resource abundance, although it had some limitations. For example, Ejina Banner has limited total water resources and an extremely small population, resulting in a large water resource per capita. This resulted in a low degree of suitability of the virtual water strategy in the Ejina Banner, whereas in reality, water resources are in great demand, especially ecological water resources. Therefore, the selection of appropriate evaluation indicators is key for eliminating some of the limitations and uncertainties. Some of the indicators used in this study were specifically designed for the HRB from an integrated water–ecosystem–economy system perspective. Many indicators were used with the evaluation index, which may result in application difficulties in areas with weak research foundation and insufficient available data. Therefore, a method with the potential to identify the suitability of the virtual water strategy for a specific region was developed in this study.

5. Conclusions

The virtual water strategy remains controversial, though having been used as a practical tool to alleviate water scarcity in some regions. For water-scarce areas, the virtual water strategy is a potential option to mitigate regional water shortages with previous successful applications in the Middle East, and irrigated crop production regions, such as North Africa. Therefore, the virtual water strategy could be tailored to specific regions and utilized specifically by them. However, the virtual water strategy is not the only method to resolve water scarcity. To achieve regional water security and ensure synergetic development of the water–ecosystem–economy system, we should establish an integrated allocation mechanism for physical and virtual water. Different polices have been established to tackle the same problem among different administrative areas. Therefore, it is imperative to evaluate the suitability of the virtual water strategy for different counties in the same river basin. This study reviewed the theory and application of the virtual water strategy. Following the review, we then constructed a comprehensive and practical evaluation index after analyzing the factors influencing implementation of the virtual water strategy from the perspective of an integrated water–ecosystem–economy system. We then applied the improved entropy weighting and fuzzy synthetic evaluation methods to determine quantitatively the suitability of the virtual water strategy for the 11 counties in the HRB.

The results indicated that the suitability of the virtual water strategy varied across the HRB. The level of suitability for almost half of the districts was excellent, while that for the other half was good or average, except for Jinta County, which was considered poor. From the perspective of industrial structure and economic development, the adoption of the virtual water strategy was considered most suitable in the counties Jiayuguan and Ejina. The results also indicated that the virtual water strategy should be implemented primarily to promote food trade among different counties within the HRB. Adoption of the virtual water strategy in suitable locations can help control physical and virtual water resources through an integrated water resource management plan. The research results show that if the poor areas promote the development of secondary and tertiary industries such as industry and service industry, it can be considered that it is promoting the implementation of the virtual water strategy, which also means it achieves the significance of the evaluation of the suitability of the virtual water strategy. In other words, the virtual water strategy has extended the solution to the water problem to the socio-economic system, and its suitability evaluation will answer the question of how to solve the problem of water resources in the socio-economic system. Obviously, in this study, through the results of the virtual water strategy suitability evaluation in the Heihe River Basin, it is clear which specific industries need to be developed in every county to maximize the effectiveness of the virtual water strategy.

Author contributions

Feng Wu designed the research topic and edited the manuscript; Xiaolin Cui contributed to the methodology of the study Xiaojuan

Wu shared efforts in data analysis and draft the manuscript; Xiaojia He analyzed the results and provided suggestions to revise the paper; Chenchen Shi revised the manuscript; and Zhe Li analyzed part of the results and edited the manuscript.

Conflicts of interest

The authors declare no conflict of interest.

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